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Technical Report No. 46

SACLANT ASW
RESEARCH CENTRE

A COMPACT THERMOMETER FOR THE STUDY OF MICROTHERMAL STRUCTURE FROM OCEANOGRAPHIC BUOYS

by

R. PESARESI and R. FRASSETTO

15 OCTOBER 1965

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VIALE SAN BARTOLOMEO, 92
LA SPEZIA, ITALY

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APPROVED FOR DISTRIBUTION

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Director

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A COMPACT THERMOMETER FOR THE STUDY OF MICROTHERMAL STRUCTURE FROM OCEANOGRAPHIC BUOYS

By

R. Pesaresi and R. Frassetto

ABSTRACT

A solid-state, thermistor thermometer, of small physical size (13 cm x 14 cm), low cost (21 dollars worth of parts), and long-term stability (of the order of 0.01°C in 60 days) is described. It has been used successfully — in vertical arrays — for the study of ocean thermal microstructure in turbulent layers. Several probes can easily be plugged in on a 5 mm diam, single conductor cable that also carries the load of a special, compact oceanographic buoy. The electronic circuit is applicable to different types of sensor (i.e. current velocity, direction meters and pressure gauges).

INTRODUCTION

A compact, oceanographic buoy system has been developed in this laboratory for the study of turbulent layer structures in transitional areas of the ocean where strong currents may be met. Sturdiness, small size, low cost and good stability were the main characteristics desired for the sensors to be suspended in vertical array from the buoy.

In this buoy system the sensors are required to make simultaneous measurements at regular intervals over long periods of time, with minimum power consumption. Among the various techniques for measuring, telemetering, and recording oceanographic variables, the most suitable seemed to be that in which a datum measurement is made proportional to a time interval between two electric pulses. This is achieved by means of a compact circuit based on an R-C timing network (the sensor providing the resistance) and a voltage sensitive switch (a unijunction transistor).

With this technique, a single conductor and sea return can be used. This permits a simple installation, in which a large number of sensors can be connected easily, both mechanically and electrically, to a single insulated wire that also forms the taut mooring cable of the buoy.

Small size was obtained by the use of miniature components and printed circuits, and by putting the circuits in epoxy resin that can be directly exposed to hydrostatic pressures. The maximum pressure reached is equivalent to a water column of 400 m. As measurements are to be made over long periods of time, stability of the circuits is an important feature, and the components have been properly selected and aged to achieve this. Among the

other characteristics that were looked for in the selection of components from manufacturers' stocks was that of minimum sensitivity to external pressure.

The buoy system is devised to permit the presentation of the pulse measurements in a sequence corresponding to the sequence of the probes on the array (first the shallowest, last the deepest). This is achieved by a staggering technique, so that each probe has its own response time, independent of the other probes. Enough pulse spacing is allowed to enable temperature-inversions at any depth to be recognised.

1. ELECTRONIC CIRCUIT

1.1 Working Principles

The working principles are illustrated in Fig. 1. Measurements are made intermittently in cycles, each of which starts when switch **S** connects a battery voltage E to the insulated mooring cable M and, hence, to the array of thermometers $T_1 \ldots T_n$, (Fig. 1a). The initial surge of current induces a voltage pulse P_o in the transformer T_R, across which a magnetic tape recorder is connected. The start of the cycle is thereby recorded as a reference pulse from which all subsequent data pulses can be measured in terms of their time intervals.

The thermometer probe circuits are based on relaxation oscillators employing silicon unijunction transistors, as illustrated schematically in Fig. 1b. When the cycle starts, and battery voltage is applied to the cable, the voltage across the capacitors C1 in each thermometer circuit T start to rise. As each capacitor's voltage V_c reaches the level V_p (Fig. 1c), its associated unijunction transistor Q1 fires, C1 is discharged, and a return pulse P_x is sent back along the cable to transformer T_R, where it induces a voltage pulse that is registered on the recorder.

For any one thermometer circuit, the time interval t_x between P_o and P_x is therefore the time taken for V_c to reach the level V_p, this being dependent on the resistance R_T of the thermistor. Thus, although all the thermistor circuits start charging simultaneously, they send back independent return pulses at time intervals $t_1, t_2 \ldots t_n$ proportional to their ambient temperatures. However, as will be explained in detail later, a staggering of the time interval scale has been arranged so that there will be no confusion

when two thermometers are reading the same temperature, or when reading temperatures through an inversion.

1.2 Actual Circuit

The complete circuit diagram is as shown in Fig. 2, which also shows the circuits for three alternative probes: for pressure or current direction, for temperature, and for current speed. These sensor circuits can be connected, as indicated, to the input of the principal circuit shown on the left of the figure, where their variable resistance is changed into a proportional time interval between pulses. If the principal circuit was in the simple form described in Para 1.1, and illustrated in Fig. 1b, there would be nothing to prevent the capacitor C1 from starting to recharge as soon as the transistor Q1 had fired. Thus, during all the time that battery voltage was applied to the cable, there would be a continuous series of return pulses from the same circuit. The complete circuit shown in Fig. 2 is designed to prevent this, as well as to prevent each return pulse from triggering other circuits on the same cable, to stabilize and filter the incoming battery voltage, and to prevent the effects of sea water potentials and temperatures.

The diagram of the principal circuit is shown divided into two parts by broken lines. That on the right corresponds to the simple form shown in Fig. 1b, except that it is R1 that carries the discharge pulse of C1 into D1, and R2 compensates for the temperature sensitivity effects. The part on the left includes all the other additions.

During operation, the return pulse P_x — arriving through R1 — triggers the silicon controlled rectifier D1, which in turn rapidly charges the capacitor C2 through diode D3 and the external circuit.

During this process, the resistor R3 limits the current passing through D1 to a value just above its "holding current"; this in turn is kept low by the resistor R4. Thus, with D1 conducting, no further pulses from Q1 can reach the cable and be registered on the recorder.

A gate circuit, made up of diode D3 and resistor R5, prevents external pulses from other thermometers on the cable from reaching D1 and influencing its holding state. Similarly, the main thermistor circuit itself is protected from these external pulses by the filter formed by resistor R7 and capacitor C3. The thermistor circuit is also kept reasonably independent of supply voltage variations, sea water paths, sea water potentials, etc. by a voltage stabilizing circuit made up of resistors R6 and R7 and the zener diode D2.

At the end of each measurement cycle the switch S is open. In each thermometer circuit all the capacitors are discharged first through the emitter of the unijunction transistor Q1, then through the resistances R_T of the probe circuits, and hence through R1, R2 and the R_{bb} of the transistor Q1. The rectifier D1 is then closed, making the circuit ready for the next measurement cycle. The presence of the monel (used as common return) in sea water acts as a weak battery, but diode D4 prevents this charge from being received by capacitor C1.

Figure 3 shows a complete measurement cycle, both in terms of the battery voltage on the cable (upper graph) and in terms of the voltage across the recorder side of transformer TR (lower graph). The pulses $P_1, P_2, \ldots P_n$ from n thermometer circuits are shown; the temperature recorded by each is proportional to the time interval $(t_1, t_2, \ldots t_n)$ between its pulse and the

start pulse P_o. With the recording system at present in use it has been found that a cycle lasting 6 sec provides the required resolution for 20 probes. The cycles can be repeated at any time intervals from 20 sec to several minutes or hours, according to requirements.

2. STAGGERING

2.1 Principle

The thermistors have a negative temperature coefficient; this means that with decreasing temperature, their resistance — and the time response of the thermometers described — will increase.

Therefore, if the temperature of the sea always decreased constantly with depth (as in Fig. 4a), a group of matched thermometer circuits arranged in parallel on an array would transmit their return pulses in the order of their depth (Fig. 3). Sea temperature, however, does not continually decrease with depth — isothermal layers (Fig. 4b) and temperature inversions (Fig. 4c) are common. In isothermal water, matched thermometer circuits would send back all their return pulses at the same time; in a temperature inversion, the deeper thermometers (Y in Fig. 4c) would send back their pulses before the shallower thermometers (X in Fig. 4c), and identification would be impossible.

To avoid these difficulties a staggering method has been used, so that the thermometers transmit their return pulses at progressively delayed times according to their depth. Call Δt this preset interval between the return pulses of adjacent thermometers on the array when they are reading identical temperatures, and call S the sensitivity of the thermometer in sec/^{o}C. Then the value of $\Delta t/S$ must be made greater than the maximum temperature inversion expected between the thermometers, if the deeper is never to send back its return pulse before the shallower. The value of Δt appropriate to any given temperature inversion conditions is obtained by the proper selection and combination of the thermometer circuit components.

The method of combining these different-sized components to obtain the required degree of staggering will be discussed in the next chapter. After assembly, the thermometers are calibrated and the degree of staggering verified. Figure 5 shows a sample of calibration curves and the values of S and Δt corresponding to one of them.

With the use of staggering it is no longer possible to use the same scale for all thermometers when interpreting the intervals between pulses as recorded temperatures. Instead, a separate scale is required for each thermometer according to its calibration curve, but this can be accomplished automatically by feeding the calibration data into the computer when the final results are being analysed.

2.2 Method of combining components

To obtain the required degree of staggering, slightly different values must be used for each of the principal components — the thermistor, the capacitor C1, and the unijunction transistor. There is no need to buy special components that differ by these small values, because such ranges are found within the ranges of tolerance quoted by the manufacturers of standard components. The standard components chosen were:

for the thermistors	-	Veco 51 A 11 100 kΩ Tolerance of $\pm$ 15% at 25°C
for the C1 capacitors	-	Mylar dielectric 15 μf, 60 v DC Tolerance of $\pm$ 10%
for the unijunction transistors	-	2N1671B Silicon Tolerance of $\pm$ 20%

In the first production, 290 capacitors, 286 thermistors and 202 unijunction transistors were bought from manufacturers' standard stocks. The frequency distribution of their deviations from quoted values was as shown in Figs. 6a, b & c respectively. If components with greater tolerance are selected, these distribution spreads can be increased and the price of components decreased.

The combination of these components to obtain the desired degree of staggering can be carried out by computer, but if a larger number of units are being assembled at once, the possibilities become too great (for 100 units there are 10^6 combination possibilities). In such circumstances — which would be the most usual — the quickest procedure is to combine the capacitor and unijunction transistor as described below, and then to let the computer combine these capacitor/unijunction transistor pairs with the thermistors (this reduces the possibilities handled by the computer to 10^4 for 100 units).

To form the capacitor/unijunction transistor pairs, the individual components are measured to within an accuracy of 1% and their values listed in increasing order. The smallest-valued capacitor is then paired with the smallest-valued transistor, and so on throughout the series. These pairs are measured in combination with a known, stable resistor. The distribution of values of the pairs is larger than the distribution of the capacitor of transistor values (theoretically it is the sum of the two distributions: $\pm$ 10% for the capacitors plus $\pm$ 20% for the unijunction transistors should give a distribution of $\pm$ 30% for the pairs). Figure 6d shows the result of combining the capacitors and transistors that were used for Figs. 6a and 6c respectively.

When the capacitor/transistor pairs are combined with the appropriate thermistors, a large range of values is obtained from which all the required degrees of stagger are possible.

3. CIRCUIT STABILITIES AND SENSITIVITIES

3.1 Long term stability

Table A summarizes the differences between two calibrations made seventy days apart. The estimated instrumental error ($\pm$ 5 m ^{o}C) — which has to be taken into account — is due to the time measuring system (automatic time interval counter-printer) and the stability of the temperature bath (Fisher isothemp bath).

The 18 thermometer circuits in Table A were used for field measurements during twenty of the seventy days that separated the two calibrations. The remaining fifty days are to be considered as shelf time.

These records refer to the first set of thermometers, made in 1963. However, in 1964, another set was made in which the components used had not been aged. Figure 7 compares the long-term stability of these two sets. Figure 7a shows the percentage distribution of deviations recorded after 70 days with the 1963 (aged components) set; Figs. 7b & c show the percentage distributions of deviations recorded after 270 and 98 days, respectively, with the 1964 (non-aged components) set. In all three cases, the period between calibrations included a period (from 15 to 30 days) of field use.

It is seen that — as is to be expected — the thermometers using aged components are more stable (80% having a deviation within $\pm$ 10 m^{o}C) than those using non-aged components. However, it is also seen that natural ageing occurs and that the stability during the second (98 day) period was proportionally greater than during the first (270 day) period. This is expressed in Fig. 7d, which compares the deviations of each individual thermometer during the two

periods. It is seen that 61% of the thermometers have a Δ''/Δ' relationship between 0 and +1, indicating a decreasing degree of deviation in the second period. Thus, especially if the deviations are acceptable for work during the first two years use, thermometers could more easily be made with non-aged components, as long as frequent calibrations are made during the early years.

3.2 Short-term stability

Short-term stability of the circuits appears to be greater than the stability of the measuring system. Table B gives the results of 20 measurements of 5 circuits, each made 5 min apart. Column (a) refers to thermometer circuits incorporating thermistors, column (b) to the same thermometer circuits where thermistors have been replaced by stable resistors.

The standard deviations σ and the differences Δ between the maximum and minimum value measured are shown in each case. The differences in values of both σ and Δ between columns (a) and (b) are probably due to non-homogeneities in the water of the calibration bath.

3.3 Temperature sensitivity

The thermometer circuits (exclusive of thermistors) are to some extent sensitive to temperature variations of the ambient. This is an effect of the individual temperature sensitivities of the three components: transistor Q1, capacitor C1, and zener diode D1 (Fig. 2).

By varying the value of resistor R2 (Fig. 2) the temperature sensitivity of the circuit can be reduced to some extent, within a given temperature range.

When a large number of components are involved, a statistical method must be used to calculate this compensation. A sample of circuits is taken and the values of R2 that minimize their temperature coefficients are measured. The average of these values is then used for the whole batch of circuits. However, before the batch of circuits is put into use, another sample is taken and tested to ensure that the chosen value of R2 has given acceptable results.

The sensitivity was found to be

$$+ \left\{ 0.48 \begin{pmatrix} +0.28 \\ -0.50 \end{pmatrix} \right\} \quad \mathrm{m}^{\circ}\mathrm{C}/^{\circ}\mathrm{C}$$

which corresponds to

$$- \left\{ 0.24 \begin{pmatrix} +0.14 \\ -0.25 \end{pmatrix} \right\} \quad {}^{o}/oo/^{o}\mathrm{C}$$

in the temperature range of 13^{o}C to 23^{o}C.

The time constant of the assembled circuits is about 3 min. Rapid ambient temperature variations can therefore introduce an error in the measurements.

3.4 Pressure sensitivity

The circuits are also sensitive to external pressure. The effect is felt mostly by the main capacitor; miniature air bubbles trapped between the mylar sheets decrease in volume and change its capacity.

Repeated pressure calibrations of the circuits, with a stable resistor substituted for the variable resistance of the probe, showed that the effect is different for each individual circuit but that calibration curves as a function of pressure are repeatable, within a temperature error of ± 4 m^{o}C.

The pressure sensitivities were measured after a short time exposure (5 min) to pressures of 10, 20, 30 and 40 kg/cm^2. Beyond this latter pressure, first the transistor and then the capacitor collapsed.

Pressure sensitivities after long period of exposure exceeding two months have not yet been measured.

3.5 Sensitivity to frequency of interrogation

Capacitor C1 of the main circuit (Fig. 2a) takes a certain time to discharge (average 20 sec) at the end of each cycle of interrogation. The next cycle can begin only after C1 is completely discharged, if cumulative errors are to be avoided.

So far, it has not been possible to increase the interrogation rate beyond 1 cycle every 30 sec, at which rate the deviation is of the order of 0.01^{o}C. Means of discharging C1 more rapidly are being investigated.

3.6 Sensitivity to power supply voltage

The response time sensitivity to voltage variations is within $\pm$ 0.2 m^{o}C/volt at the normal voltage (24 v DC).

The maximum allowable deviation of 10 m^{o}C is reached below 18 v DC.

4. PHYSICAL CONSTRUCTION

Figure 8 shows the complete thermometer unit, as attached to the mooring cable. It is 13 cm long and 4 cm diam.; in air it weighs 120 gm and in sea water 60 gm.

The internal arrangements are shown in Fig. 9. The thermistor bid tube (1) is embedded to half its length in a capped Vinyl tube (2) filled with Araldite. The length by which it projects has been determined by tests, which show that at least 1/2 cm of the glass root below the bid must be exposed to water for effective heat dissipation. The bid is protected by a wire guard (3).

The Vinyl tube slides into a shock-absorbing rubber mounting (4) made in a conical shape so that the bid has maximum, undisturbed exposure to the current.

The thermistor is connected electrically to the rest of the circuit by flexible wires long enough to permit several renewals of this fragile unit. The rest of the circuit is potted in a PVC tube, into which the base of the rubber mount fits; to take care of the different water compressions all the intervening space is packed with Vaseline through the two buffer holes.

More than half of this tube is occupied by the main Mylar dielectric 15 μf capacitor (C1 in the circuit diagram), held in a central position by four spacers. Below this are the remaining electronic components mounted on a circular printed circuit. The base of the tube is closed by a neoprene end-plate with a tapered wire protection. All the contents are potted in Araldite.

Electrical connections between the thermometer unit and the recorder are (1) through an electrical outlet on a single neoprene coated wire rope of high tensile strength and good flexibility and (2) by a Monel sheet riveted around the PVC tube, which acts as the conductor for sea return. The deep-sea connector for the probe passes through a tapered neoprene reinforcing sleeve.

These thermometer units have been exposed to mechanical and thermal shocks and to vibrations of up to 100 cps without any change in their original calibration curves.

Figure 8a and c show how the ground soldered contact is imbedded in the Araldite to prevent exposure to water and galvanic corrosion.

CONCLUSIONS AND RECOMMENDATIONS

Over 100 thermometers have been made at the Centre and used for field measurements from the Centre's oceanographic buoys for periods of from 15 to 30 days at a time. They have demonstrated that, with a few improvements, the system is capable of recording temperature profiles with an accuracy of $\pm 0.01^{\circ}C$.

A constant error was given by pressure, but a correction appropriate to the working depth of each thermometer was applied before data processing. The maximum depth for the electronics described in this report is 400 m.

However, it has been found that with long exposure to sea pressure — after several periods of field work — the surrounding epoxy resin shows signs of fatigue, as a result of which about 30% of the thermometers used in a recent cruise (GIB V) were found to be shorted. It has therefore been decided to enclose later models in stainless steel or titanium tubes closed by PVC end-caps. This will keep the circuit at atmospheric pressure, and will also permit further reduction in the size and weight of the probes, because components can be chosen for their small size rather than for their lack of pressure-sensitivity. Because of its temperature sensitivity, the circuit will then have to be potted in a silicone compound within the metal tube. This will provide the greatest possible thermal conductivity and thereby keep the circuit at the external ambient temperature. If this is not done, there would be a risk of uncontrollable errors when there are rapid temperature variations in the water.

Although the circuit described is designed for a 30 sec minimum interrogation rate, it would require only the changing of a few critical components to make it suitable for faster rates. In such a case, of course, the recording system would have to be of a type that would permit adequate resolution.

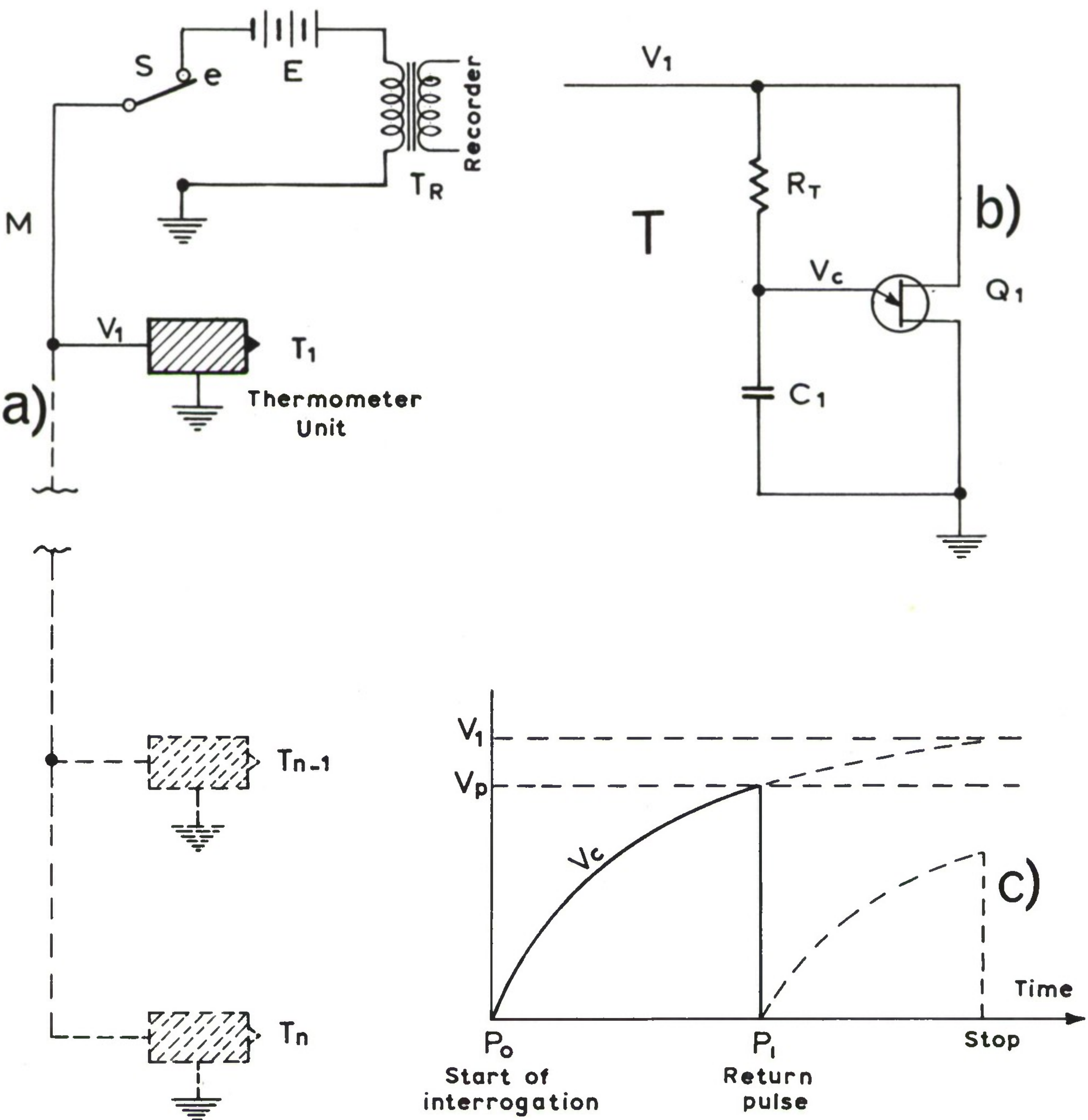

FIG. 1 WORKING PRINCIPLES OF THE ELECTRONIC CIRCUIT

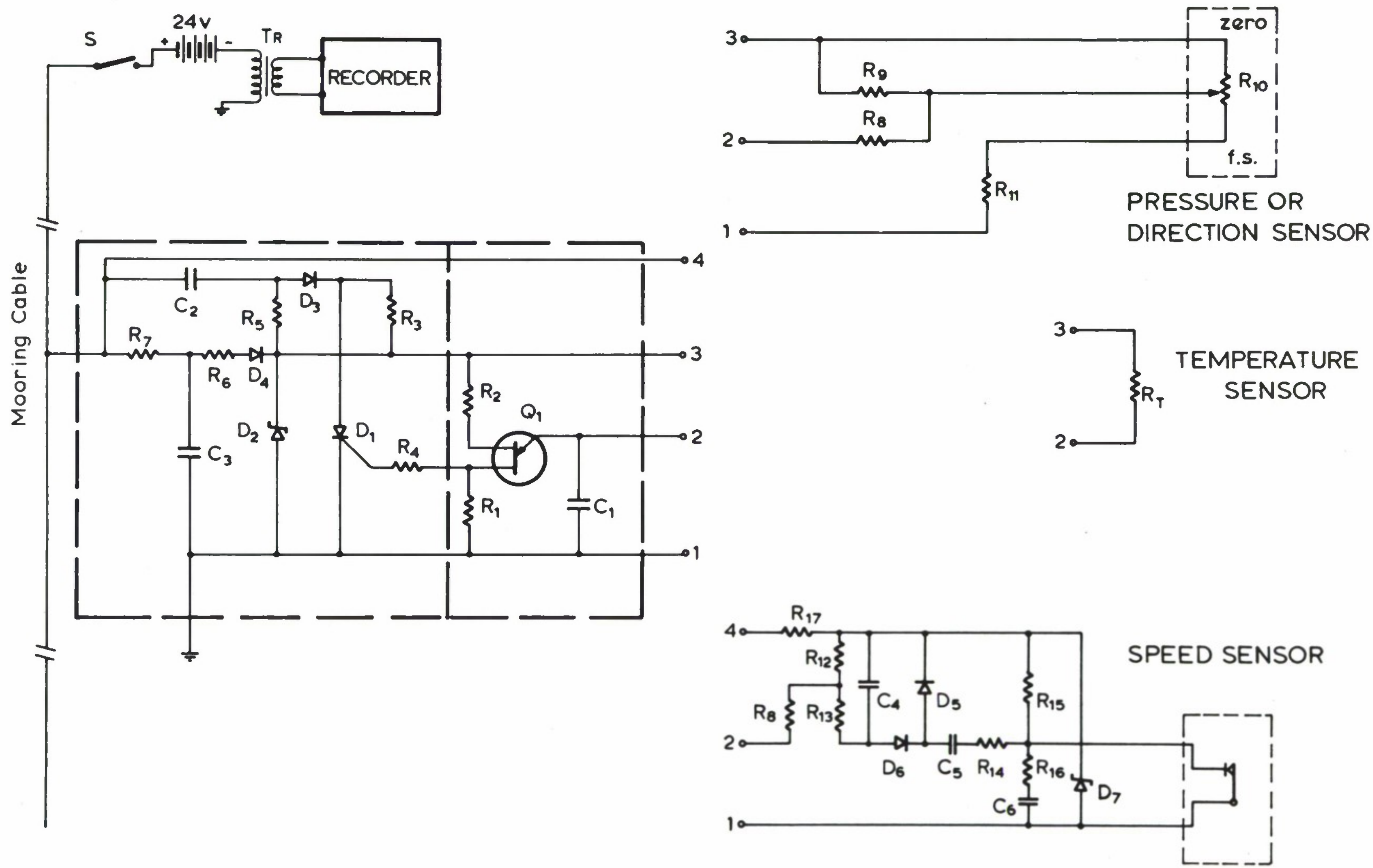

FIG. 2 CIRCUIT DIAGRAM, SHOWING THREE ALTERNATIVE SENSORS

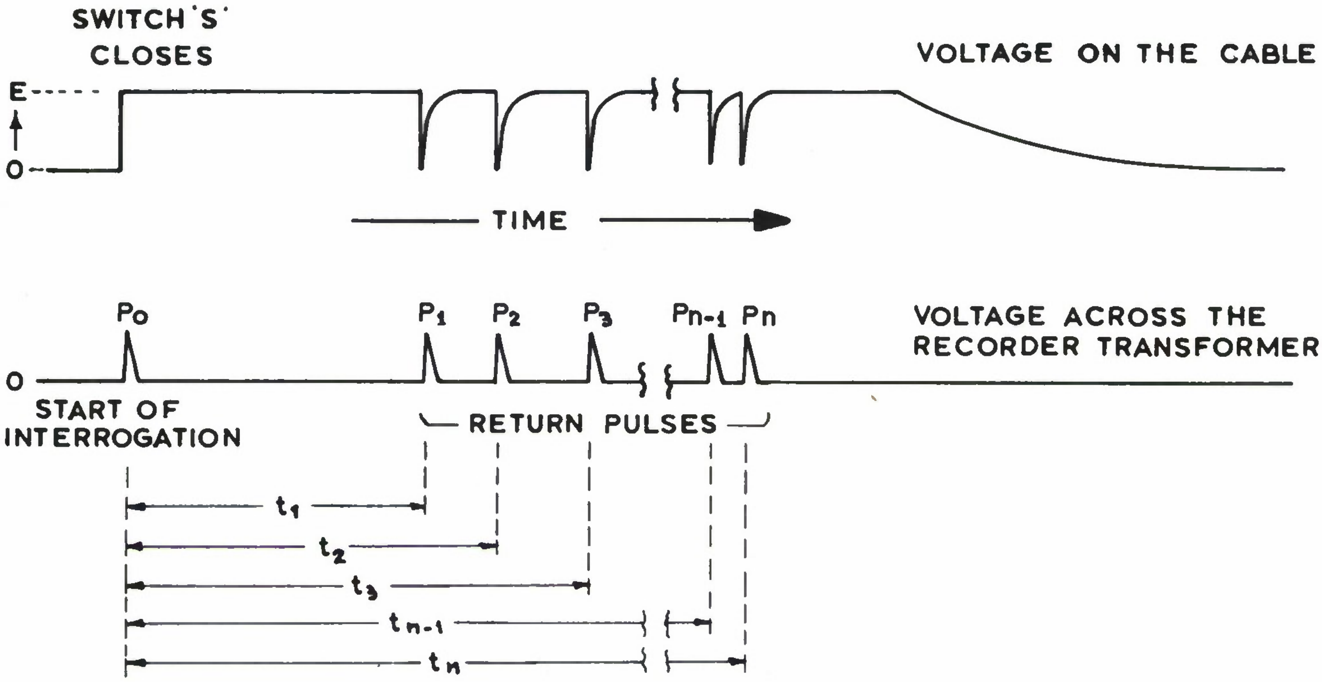

FIG. 3 COMPLETE MEASUREMENT CYCLE IN TERMS OF BOTH VOLTAGES

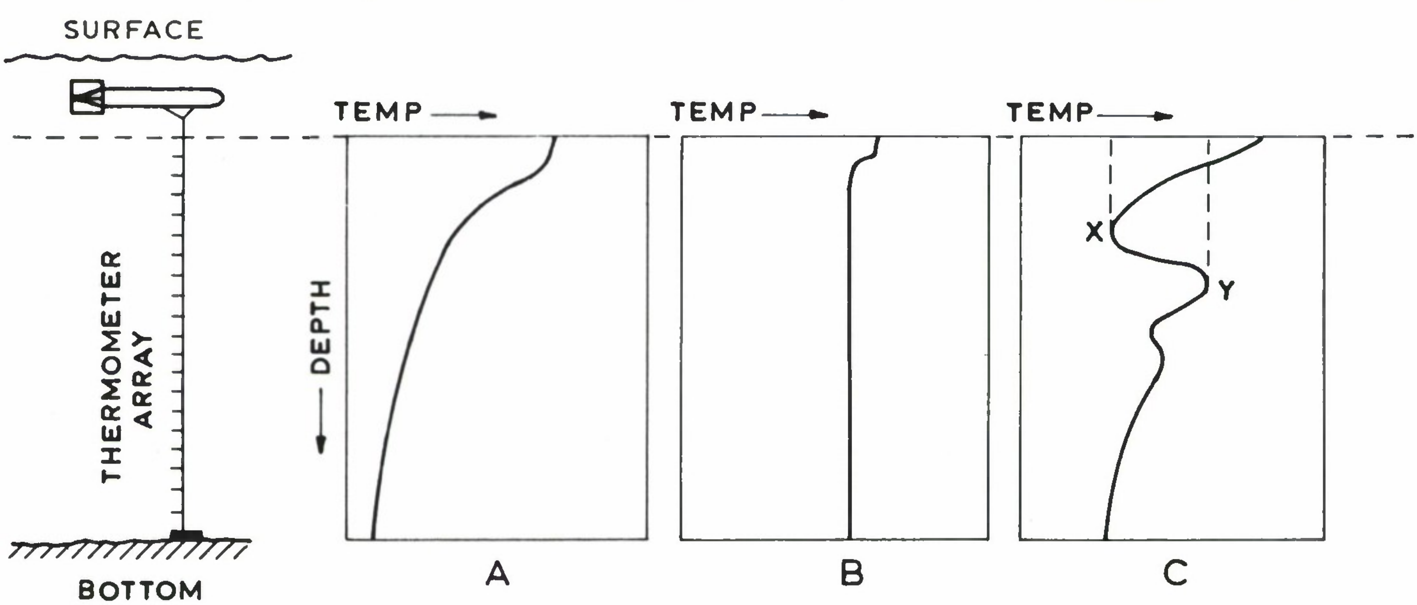

FIG. 4 MEASUREMENTS IN DIFFERENT WATER TEMPERATURE PROFILES

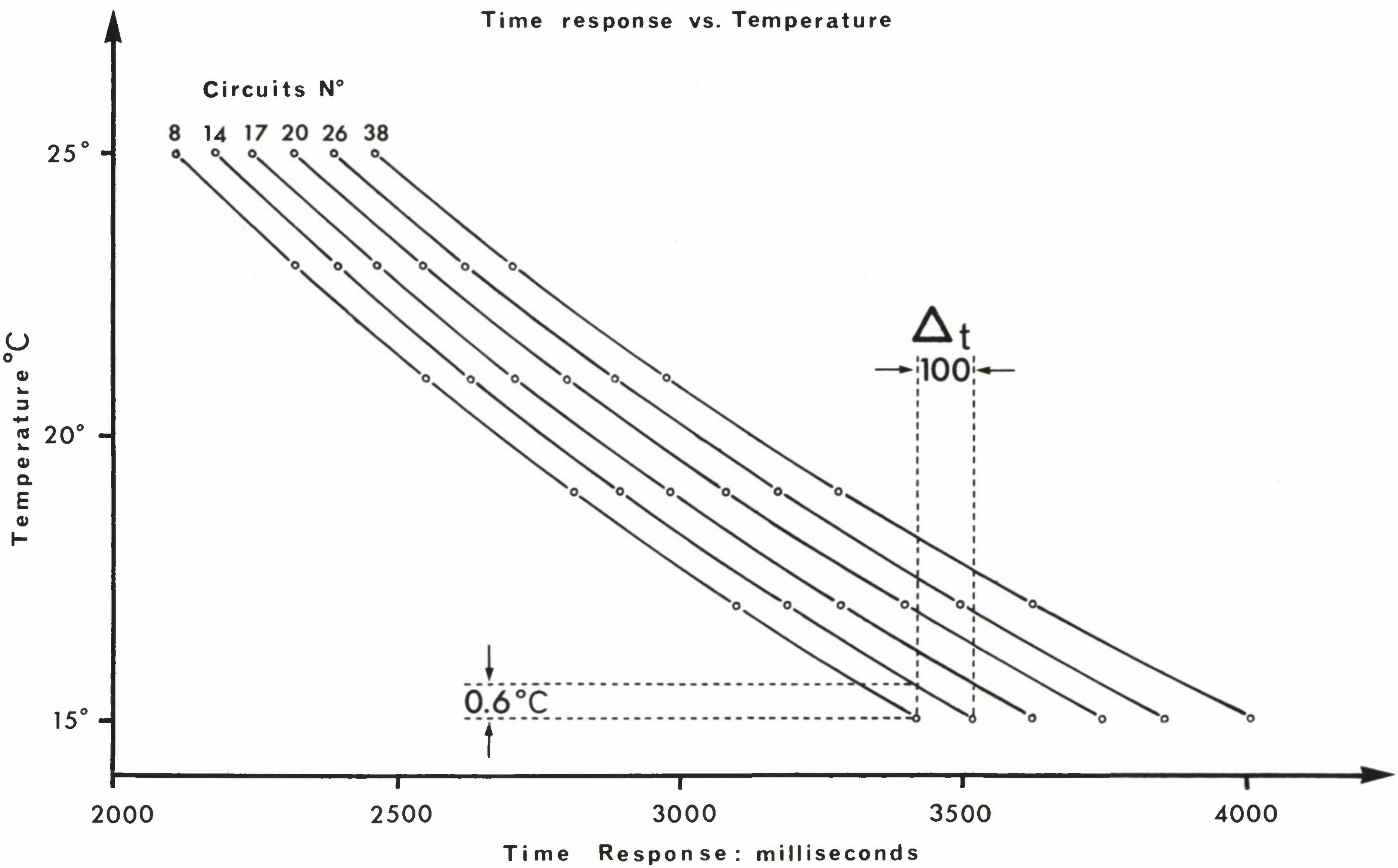

FIG. 5 CALIBRATION CURVES OF THERMOMETERS

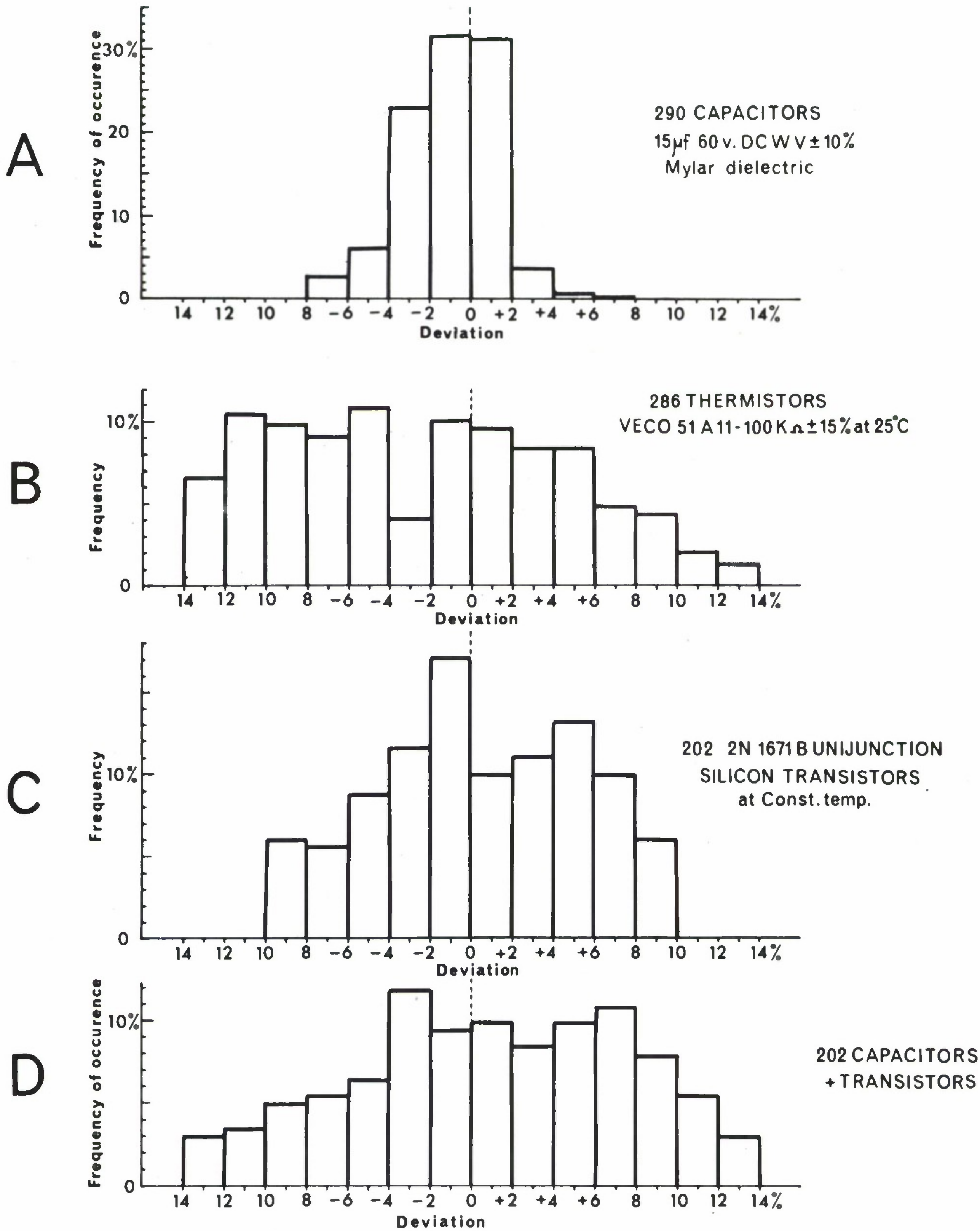

FIG. 6 FREQUENCY DISTRIBUTIONS OF DEVIATIONS FROM QUOTED VALUES

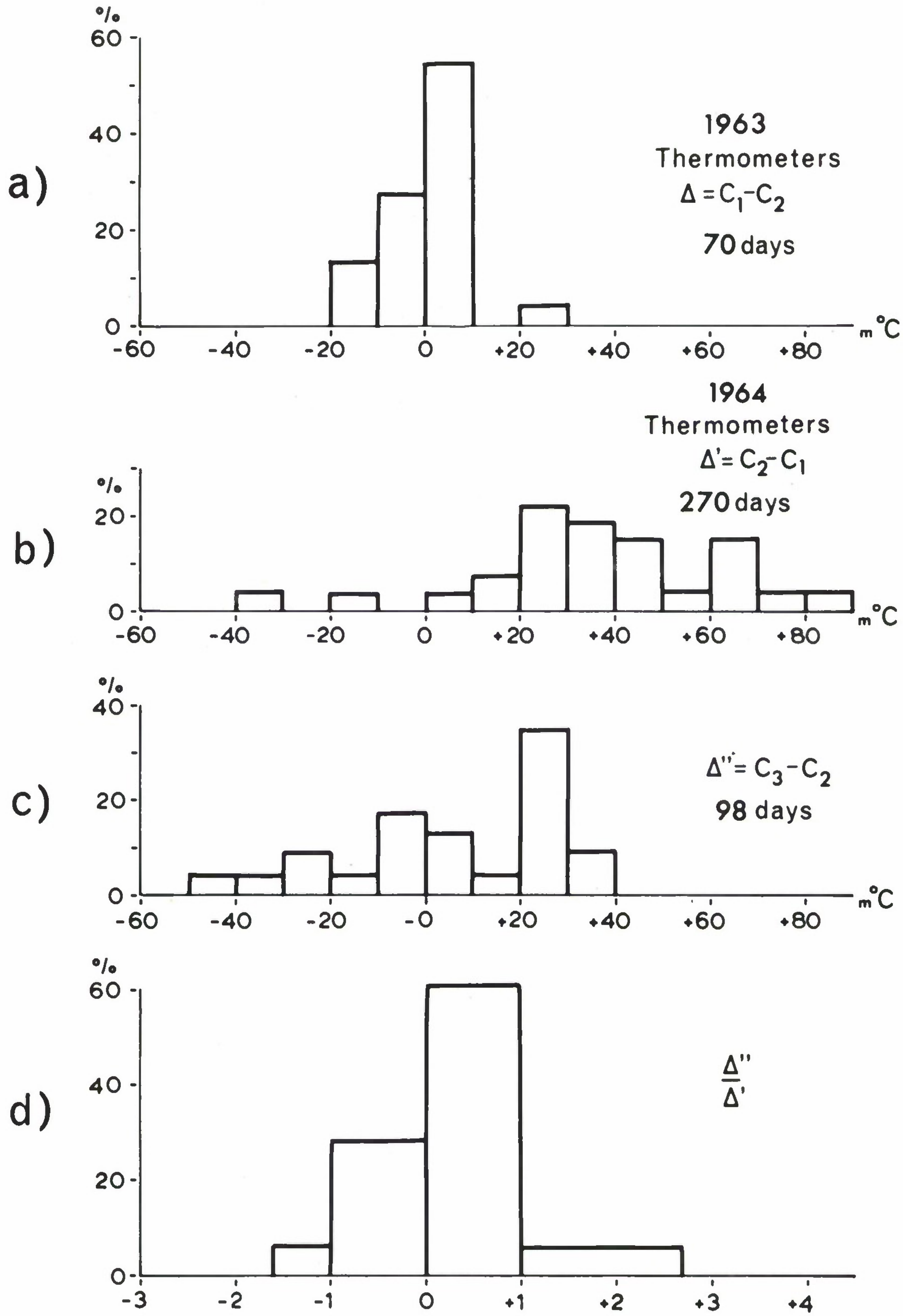

FIG. 7 COMPARISON OF LONG-TERM STABILITY BETWEEN TWO SETS OF THERMOMETERS

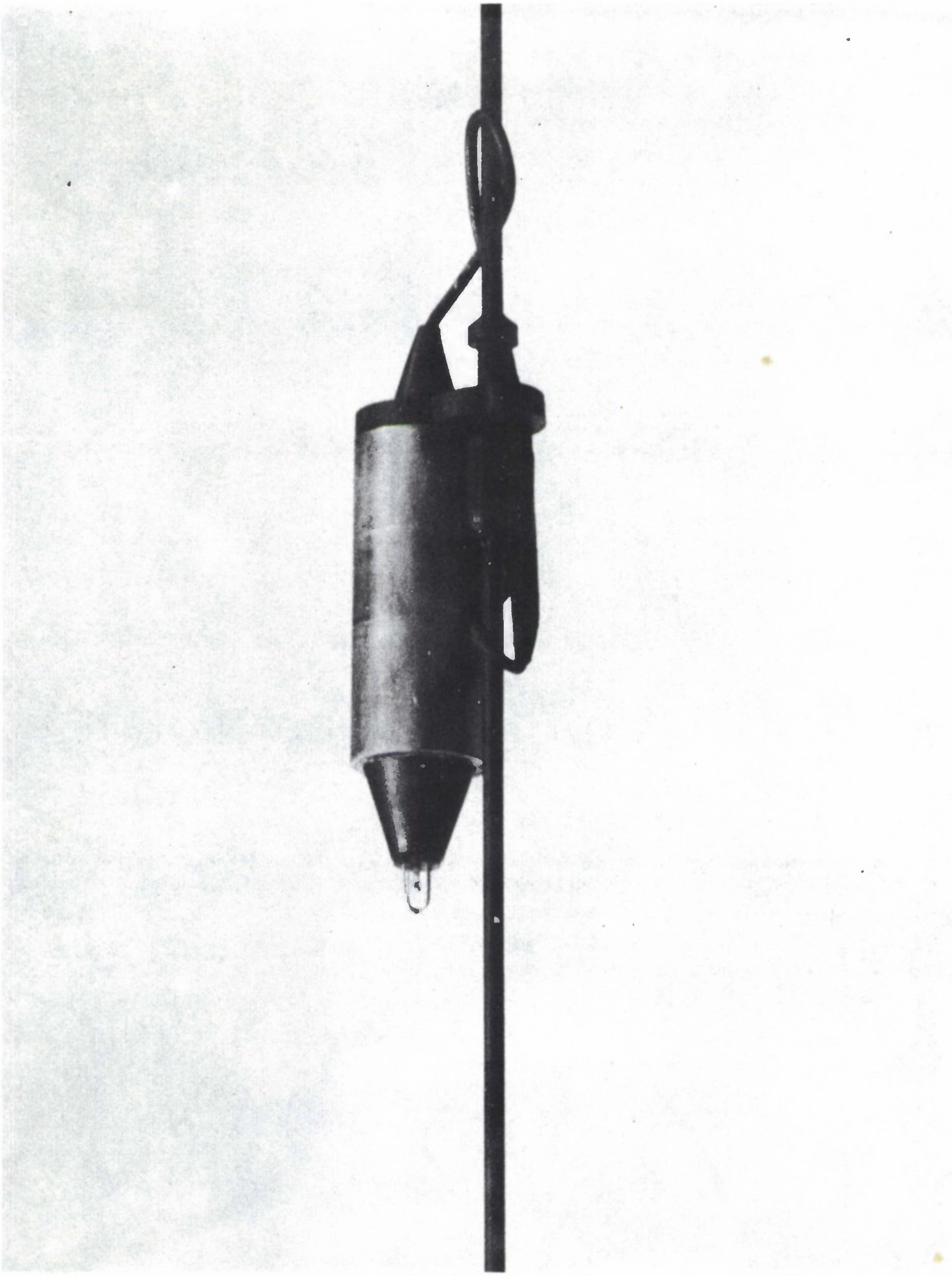

FIG. 8 PHOTOGRAPH OF A COMPLETE THERMOMETER UNIT

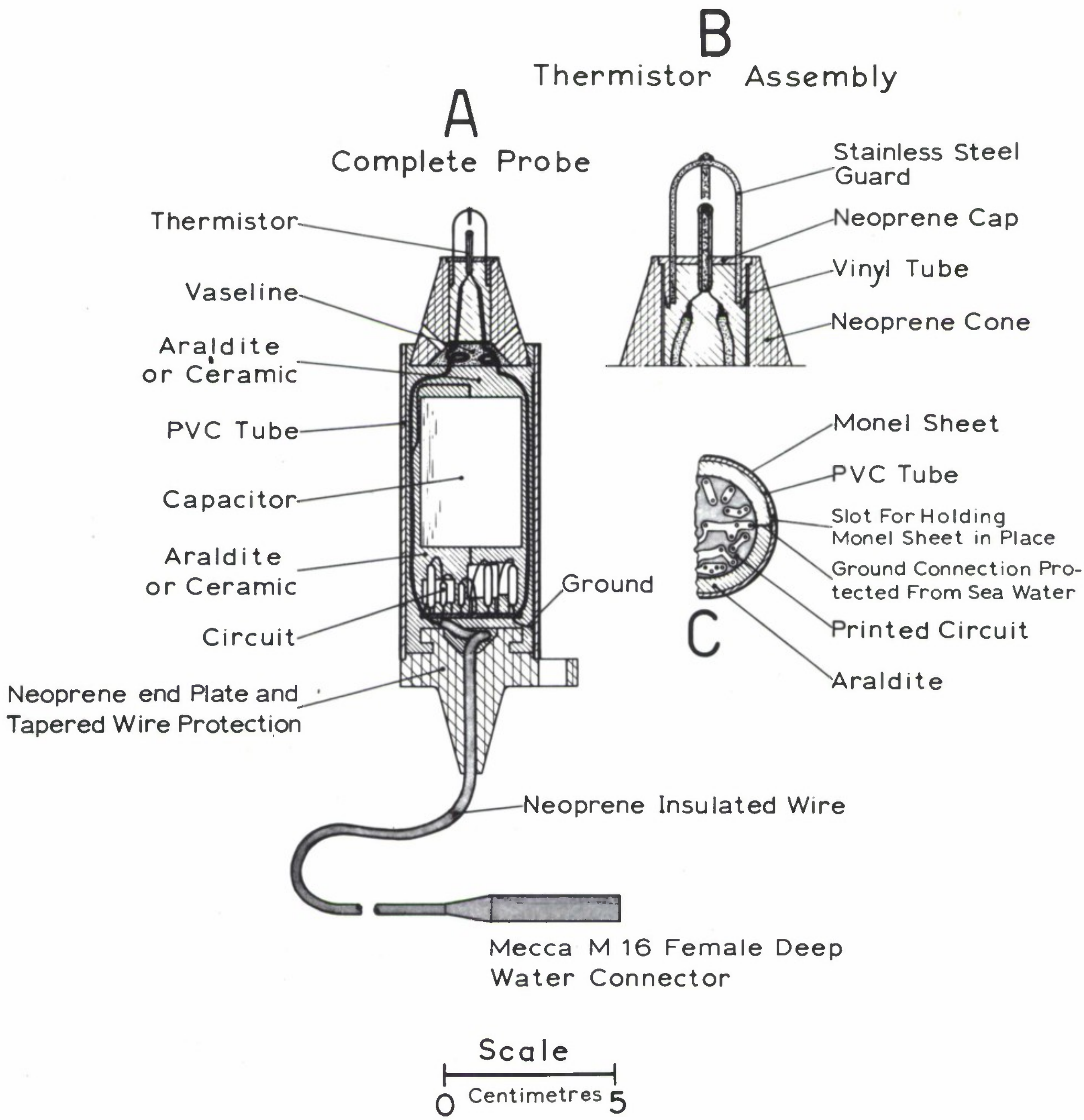

FIG. 9 THERMOMETER – CROSS SECTION VIEW

TABLE A

Long-term stability

CIRCUITS	TEMPERATURE °C					
N°	15°	17°	19°	21°	23°	25°
1	1.4	4.8	0	2.6	5.0	3.2
2	6.4	2.8	4.6	2.6	0	−7.2
3	−10.0	−7.4	−6.8	0.8	−0.8	0
4	−16.2	−14.6	−16.0	−14.8	−16.8	−12.4
5	4.8	12.6	8.6	7.6	9.8	12.2
6	1.8	6.0	5.8	4.0	5.4	6.8
7	21.4	26.6	26.8	28.4	29.4	34.4
8	−5.2	−2.8	−1.8	−0.6	−2.2	−3.4
9	20.4	14.4	13.4	12.8	9.6	9.0
10	−1.6	−0.4	−1.4	1.0	0	4.4
11	−8.6	−12.0	−13.4	−11.0	−10.2	−9.8
12	−0.6	0	1.2	5.8	2.8	5.2
13	−9.0	−8.2	−9.4	−9.8	−10.0	−9.2
14	1.2	2.4	2.6	2.8	8.2	9.2
15	−4.8	−8.2	−5.8	−8.4	−9.8	−3.8
16	6.4	6.6	9.6	6.8	3.4	9.0
17	0.4	3.6	2.8	4.2	5.2	6.6
18	−11.6	−9.6	−12.0	−8.2	−5.2	−6.6

Deviations in temperature readings after 70 days exhibited by a typical batch of thermometers (expressed in m°C ± 5 m°C)

TABLE B

Short-term stability

Circuits	a) with thermistor		b) with resistor	
N°	σ	Δ	σ	Δ
1	3.4	7.0	2.2	4.6
2	1.4	5.0	0.8	2.6
3	0.8	2.4	0.4	1.4
4	0.8	3.0	0.4	1.8
5	1.4	5.4	1.0	3.6

Deviations expressed in m°C ± 5 m°C

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